# ADVANCED LINEAL GENERATORS: PROOF OF CONCEPT

Final Report

SAIC-97/1060

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13. ABSTRACT *(Maximum 200 words)*
SAIC, in association with O'Neill Development Company, completed a proof-of-concept study of a unique engine-generator system that uses opposed cylinders to drive a common piston linearly back and forth through a solenoid. We found that the basic concept of the "lineal generator" is viable. It offers a number of advantages: its relatively simple design will result in improved mechanical robustness and cost savings, and it is easily customized to specific applications. There are a number of challenges that must be addressed: for example, the lack of rotational components makes starting the device mechanically difficult, structural alignment is critical, and balanced engine and load parameters are crucial. Though the levels of complexity are different, each can be successfully addressed through careful component design and engineering. Because this technology offers such promise, SAIC is continuing development of the device for commercial applications.

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## INTRODUCTION

SAIC, in association with O'Neill Development Company, has completed a proof-of-concept study of a unique engine-generator system. This system is known as a lineal generator and is based on a reciprocating twin cylinder engine concept in which a single piston is driven back and forth between opposing cylinders following a two-stroke cycle. Attached at the center of the piston is a magnetic assembly. The oscillating motion of the piston drives the magnet assembly back and forth through corresponding solenoid coils. The magnet polarization and the spacing of the magnets and coils are configured to produce electrical power with each oscillation of the piston. Our study has found that the basic concept of this lineal generator is viable. We also identified several areas that require further development to reduce the concept to a working prototype.

This final report covers the design, assembly, test, evaluation and commercial potential of the lineal generator as a proof of concept. Section 2.1 discusses the basic design of the engines used in this project. Section 2.2 addresses the operation of these engines in the lineal generator configuration and Section 2.3 covers the design and testing of the solenoid subsystem. Section 2.4 explains the engine and engine-generator tests performed during this work. Sections 3 and 4 summarize our conclusions and recommendations, respectively.

## 1.0 Statement of the Problem

The SAIC lineal generator research project was performed in response to a DoD need for compact power generation equipment for a variety of applications. DoD requirements range from very small systems for future applications such as the mobile electric soldier, to direct replacement systems for auxiliary power units. The performance of all military systems are similar in that they need to be exceptionally robust, and as compact and lightweight (low burden) as possible. For most applications within the DoD, fuel consumption and power output efficiencies are also paramount. The logistics planning for power system support such as maintenance, fueling, and transport are also important issues. This is especially true as the Army moves toward implementation of a one-fuel-forward policy.

SAIC developed the lineal generator concept with focus on:

- scaling to sizes appropriate to specific applications;
- meeting the criteria of running on diesel fuel (DF-2);
- providing reliable power with low maintenance;
- having a low burden (i.e., compact and lightweight); and
- matching or exceeding current power output to fuel consumption efficiencies.

To accomplish these tasks, we designed and fabricated a basic unit with the goal of providing a 28V 500-1000W battery charger.

## 2.0 Summary of Technical Approach and Most Important Results

### *2.1 Engine Design*

Our system offers a high ratio of power output to package burden. Because the lineal generator is based on a simple reciprocating free-piston engine principle, the number of engine components is minimal. This results in a significant reduction in both the size and weight of the device when compared to conventional engine-generator technologies. For example, a Honda 1000EX hobby generator is rated at 900W in a package that is 16.9" x 11.4" x 15.4" and weighs 57 lbs without fuel[1]. We project that an equivalent 900W output lineal generator could weigh as little as 5 lbs in a 13" x 7" x 4" volume. This represents an improvement of a factor of 100 in the power to weight-volume ratio.

The lineal generator's relatively simple design should result in improved mechanical robustness, cost savings and improved manufacturability. The improved robustness would be attributable to fewer moving parts, rigid piston, no rotational parts or joints, and fewer wear points. The potential cost savings and ease of manufacture would result from a reduced number of parts, reduced complexity, and reduced in bulk material. Additionally, the design allows for easy customization to specific applications needs. User-defined operational requirements such as specific fuel types (e.g., gasoline, diesel fuels, natural gas, isobutane) and voltage (d.c., a.c., single-phase, three-phase, etc.) could be readily incorporated into the base design.

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[1] See http://www.dct.com/motorsports/portable/specification.html

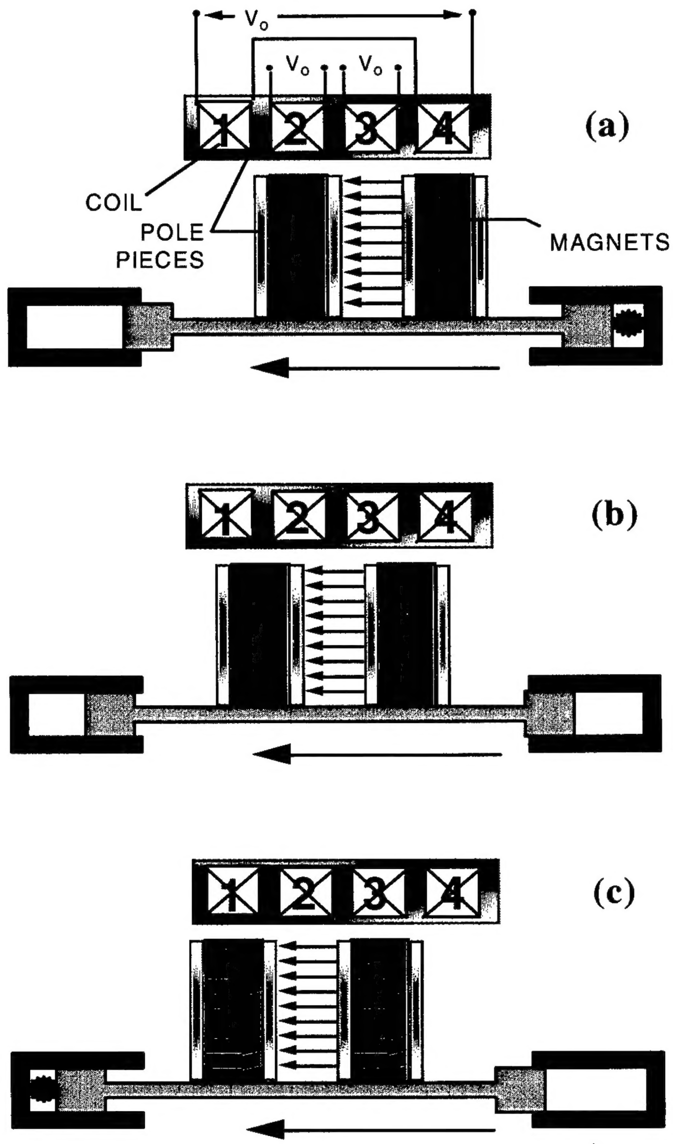


*Figure 1 . The lineal generator cycle. The stroke length of the engines determines the optimum spacing for the solenoid-coil elements. In position (a), the magnetic fields in the interior of coils 1-4 are 0, $B_0$, $-B_0$, and $B_0$, respectively. At the opposite end of the cycle shown in position (c), the magnetic fields in the interior of coils 1-4 are $B_0$, $-B_0$, $B_0$, and 0. The "end" coils 1 and 4 therefore see an oscillating magnetic field amplitude $B_0$, while coils 2 and 3 see a field oscillation of twice that magnitude.*

The many advantages of the lineal generator design are not without a price. The lack of rotational components makes starting the device mechanically difficult, structural alignment of the device is critical, and balanced engine and load parameters are crucial to engine operation. While varying in complexity, the solution to each of these issues can be realized through careful design of components used in the device.

The engine (driver) for the lineal generator is based on a twin opposed cylinder, free-piston design. For this effort, model aircraft engines were used as the basic building block for the lineal engine design. The logic behind this approach was that these two-stroke, diesel-cycle small engines are well developed, available in a wide range of powers

outputs, have the highest power output per liter of any standard engine on the market today, and are inexpensive. Also, SAIC is aware of the of DoD interest in establishing and maintaining a "one fuel forward" policy, and that the fuel of choice is diesel (DF-2). This aided our decision to base the units on engines from the model aircraft industry. There are aftermarket kits that convert these diesel cycle engines from a methanol and nitromethane mix to a kerosene and ether mix. This fuel has properties similar to JP-4. The conversion kits "up" the horsepower generated by the engines by as much as 90% . This increase is due to the energy density difference between the fuels. We reasoned that inserting the aftermarket kits would make converting the lineal engine to diesel fuel straightforward and provide a path to higher output power with the same package burden.

The cylinders, pistons, glow heads, reed valves and carburetors used in the proof-of-concept devices were a direct insertion from the hobby industry. In particular, the Cox engine designs were chosen because they are manufactured with the crankcase and cylinders as separate components. Most other manufacturers cast the cylinder and crankcase as a single unit. The removable cylinders of the Cox design allowed the direct use of these components in the proof-of-concept devices. In each model, two cylinders were mounted horizontally across from one another on a "U" shaped solid aluminum frame. Machined into each side of the frame was an air-fuel mix gallery and shaft-bearing housing. The reed valves and carburetors from the Cox engines were directly attached to sides of the frame at the mix galleries, making the frame an integral component of the engine. We adapted two standard Cox pistons for use in the lineal engine by attaching them with a straight connecting rod. The connecting rod made the pistons, in essence, a single unit. The length of this single piston was designed to match the top dead center separation of the cylinders, minus the stroke length of the engine. In the first model, built for engine only tests, the connecting shaft had an aluminum mass representing the magnetic core attached in the center. In later models, the shaft contained the magnets and pole pieces of the generator core as well as overrun stops (see the lineal engine illustration, Figures 2 and 3).

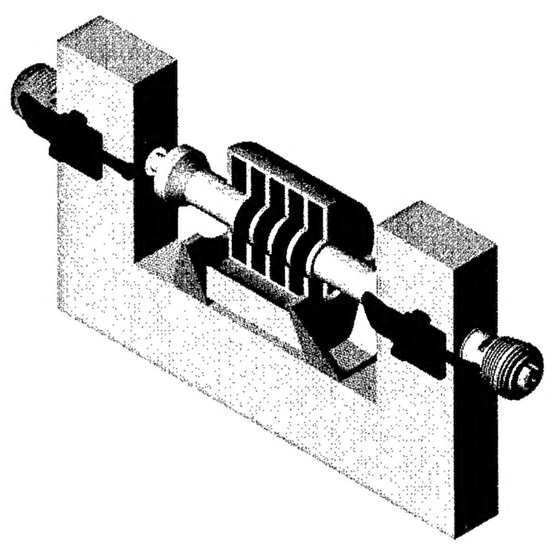

*Figure 2. Cutaway view of lineal generator showing coil assembly in position around magnetic piston.*

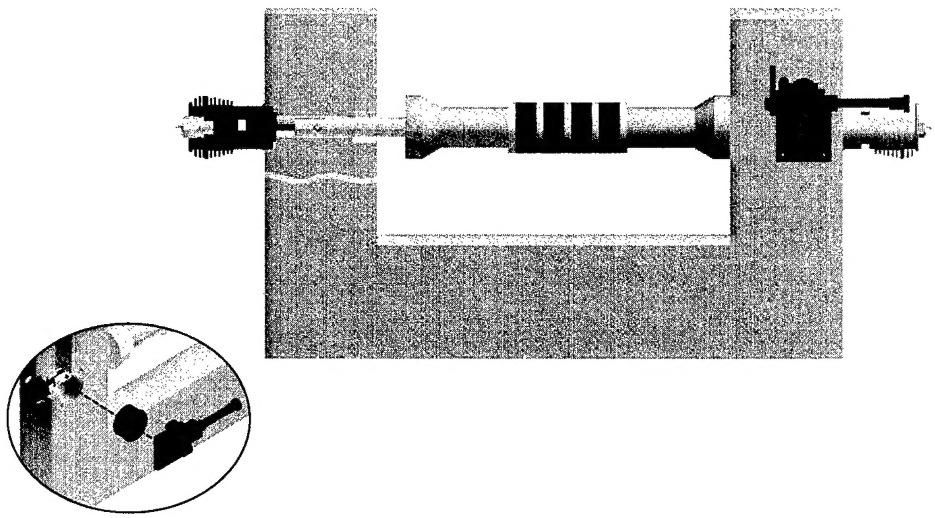

*Figure 3. Lineal generator with coil removed. Insert shows carburetor reed value assembly. Note frame "bumpers" on piston.*

We briefly examined COTS noise abatement systems as part of the engine design. This effort benefited from the widespread institution of noise ordinances in urban areas. Effective muffler systems for model engines are now available from both original equipment manufacturers and after-market vendors. An initial measurement of the noise output from a Cox 0.074c.i. *Queen Bee* at a distance of six feet was found to be 75 dB without a muffler. The same engine operating under the same conditions measured less than 67 dB when a Cox standard muffler was installed. Though no noise measurements were made of the lineal engine, we estimated that COTS muffler systems would reduce the overall noise output of a lineal generator by 11dB when compared to a unmuffled system. With proper vibration isolation and a good muffler system, the expected noise output of the lineal generator is about 60 dB. This is comparable to commercially available units.

### *2.2 Engine Operation*

The lineal engine cycle can be explained in terms of the basic small-volume, single cylinder, diesel two-stroke operation. The lineal generator operation differs only in that the cylinder on the opposite side of the frame is 180° out of phase from the side being described.

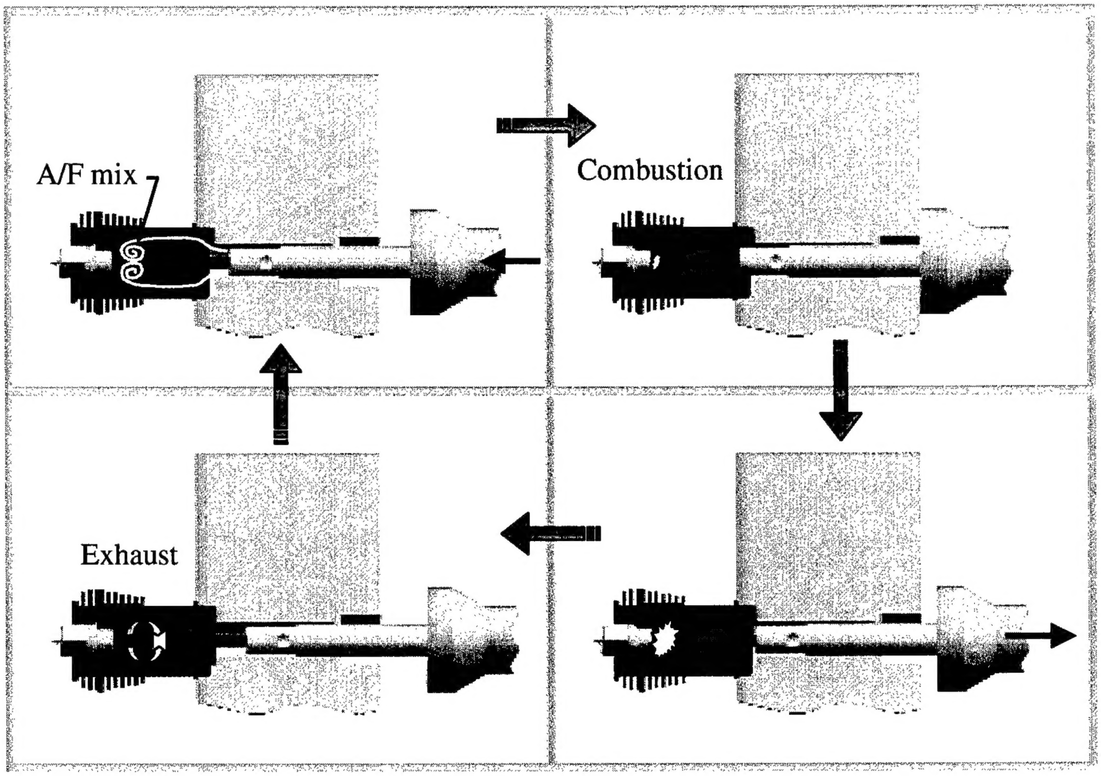


*Figure 4. Two stroke diesel cycle in lineal generator configuration.*

Assuming the glow plugs are hot and the cylinders are primed (charged with fuel and air), and that the piston is at the bottom of its travel within the cylinder in question, the following occurs (see figure 4):

1. Accelerating the piston from the bottom of the stroke towards the top of the cylinder brings fuel and air through the carburetor into the mix gallery. This is accomplished by the suction created on the backside (skirt) of the piston as it moves away from the mix gallery, deeper into the cylinder. The suction opens the reed valve, drawing in the air and fuel.

2. At the same time the fuel and air mix is brought in through the carburetor, the top of the piston is compressing the fuel and air mix within the combustion chamber (cylinder). Once the heat generated by the compression (and initially, the glow plug) reaches a high enough temperature, the fuel-air mix combusts, accelerating the piston back to the bottom of the cylinder.

3. As the piston travels back, the pressure generated by the inside of the skirt closes the reed valve and compresses the fuel and air mix in the gallery. During this stage of the cycle, the piston moves past the exhaust ports in the side of the cylinder expelling the exhaust gases.

4. Once the top of the piston has cleared the exhaust ports, it moves past the intake passages on the inside of the cylinder wall. The compressed mix in the gallery is forced to the top of the piston where the cycle starts over.

## *2.3 Solenoid Design and Optimization*

The optimization of the solenoid subsystem performance in the free piston lineal generator is based on understanding the fundamentals of how the generator provides power to the core. The forces on the pistons are equivalent to ideal springs if: 1) the origin of a linear coordinate system is in a position where the free piston is centered between the cylinders, and 2) we consider the ideal gas force associated with the compression of the gas in each cylinder in the absence of combustion. Consider initially just the ideal gas force associated with the compression of the gas in each cylinder. In the absence of any firing or exhaust cycle, the cylinders act like ideal springs

$$\begin{aligned} &F_{gas} = -kx \Rightarrow \\ &x = x_0 \sin(\omega t) \quad ; \omega = \sqrt{k/m} \\ &v = x_0 \omega \cos(\omega t). \end{aligned} \tag{1}$$

During the compression cycle of each cylinder, the fuel air mixture starts at approximately room temperature. When the ignition pressure in the diesel cycle is exceeded, the temperature and pressure of the enclosed gas rise dramatically. The power provided by the cylinders to the system is therefore slightly out of phase with the position of the piston:

$$\begin{aligned} F_{eng} &= F_0 \sin(\omega t - \delta) \\ &= F_0 \sin \omega t \cos \delta + F_0 \cos \omega t \sin \delta. \end{aligned} \tag{2}$$

Note that the power delivered to the free piston is given by

$$\begin{aligned} \langle P \rangle &= \langle \mathbf{F} \bullet \mathbf{v} \rangle \\ &= \tfrac{1}{2} F_0 x_0 \omega \sin \delta \\ &\cong \tfrac{1}{2} F_0 x_0 \omega \delta. \end{aligned} \tag{3}$$

Some obvious engine properties are evident in these equations:

- if the cylinder fires too early (timing too advanced) then it does not supply adequate power to the shaft. This can be the case if the throw of the free piston causes over-compression of the fuel-air mixture in the cylinder or the cylinders are overheated
- a lighter free piston accelerates faster, has a larger $v_0$, and couples out a larger fraction of the cylinder firing power.

When a series of magnets that are coupled to a corresponding set of output coils are added to the free piston, an additional drag force is added to equation (3). The drag force acts in a direction opposite to the velocity and is given by

$$F_{gen} = -P_{out} / v \tag{4}$$

where $P_{out}$ is the output power from the generator coils. For a set of solenoidal coils

$$P_{out} = \frac{V^2}{R_{load}} = \frac{N^2 B_0^2 A^2 \omega^2}{R_{load}} \cos^2 \omega t, \tag{5}$$

where $N$ is the number of turns in each coil, $B_0$ is the amplitude of the oscillating magnetic field, $A$ is the cross sectional area of the oscillating magnetic flux through the core of solenoid, $\omega$ is the frequency of the oscillation, and $R_{load}$ is the resistance of the load connected to the generator coils. Using the earlier expression for $v$, the drag force represented by the power out-take of the generator coils is given by

$$F_{gen} = -\frac{\omega}{x_0}\frac{N^2 B_0^2 A^2}{R_{load}}\cos\omega t. \tag{6}$$

Note that the drag force due to the power generation in the coils is in phase with the power input from the cylinders.

The total force on the free piston is given by the sum of the forces from the cylinders, the generator coils, and any frictional drag

$$F_{TOT} = F_0 \sin\omega t + \left( F_0\delta - \frac{\omega}{x}\frac{N^2 B_0^2 A^2}{R_{load}} - F_{drag} \right)\cos\omega t. \tag{7}$$

So long as the cylinders provide sufficient power to the piston that the term in parentheses is positive, the generator will continue to run at an approximately constant frequency. Excess input power will appear as additional heating of the cylinder structures and slightly increased operating frequency. Insufficient power from the cylinders will immediately stall the engine.

The free piston assembly includes the two piston heads (one for each cylinder), the connecting rod, the magnets that oscillate between output generator coils, and the pole pieces that optimize the magnetic circuit. The free piston assembly sometimes also includes a rotary gearing system to act as both a regulator on the throw of the free piston and as a coupler for a starting system. In the experiments reported here, each piston head weighed approximately 5 gm and the connecting structure weighed an additional 10-40 gm, depending on its configuration.

The oscillation frequency of the free piston assembly and the operating frequency of the generator scales as $(M_{free\ piston})^{1/2}$, as derived in Figure 5. The maximum energy output of each cylinder is approximately constant per cycle, and therefore scales approximately linearly with frequency. The maximum output power of the lineal generator therefore also scales as $(M_{free\ piston})^{1/2}$, also shown in Figure 5. It is important to note that larger engines not only accommodate a larger mass on the free piston shaft for the same frequency of oscillation, but also provide greater energy per firing cycle.

The remainder of the load on the free piston is the magnet assembly, which also determines the maximum electrical performance of the generator. The magnet assembly was illustrated in previous figures. The magnet material is SmCo-26 because of its high resistance to demagnetization, its excellent performance at high temperature, and its high remnant magnetism. The diameter of the magnets is determined by a tradeoff analysis of the demagnetization factor for the specific geometry vs. the increased magnetic flux of a larger area magnet. Finally, the maximum number of magnet-pole piece cells is deter-

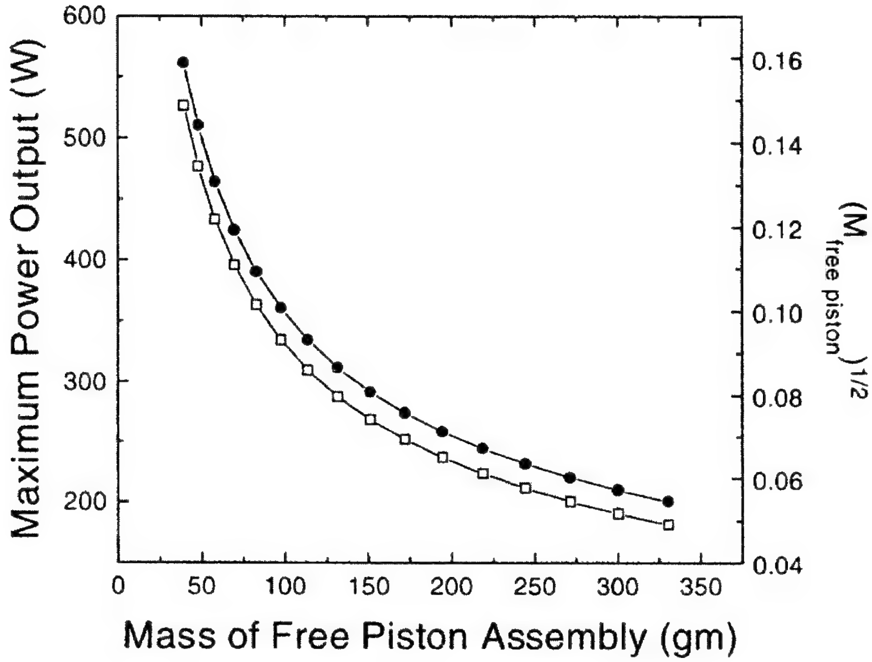


*Figure 5. A plot of the estimated maximum power output from a generator powered by two Cox 210 Tee Dee 0.090 in$^3$ engines vs. the mass of the free piston assembly. The second plot (in red) clearly shows the scaling of the power output with the inverse root of the free piston mass. The estimated maximum power output does not account for losses in the generator coils.*

mined in concert with the generator coil design by a tradeoff analysis of the allowable mass on the center shaft versus the mass and resistance of the required generator coil set.

The demagnetization factor for a general geometry is a complicated numerical calculation beyond the scope and interest of this work. A good working approximation is the formula for the demagnetization factor of an oblate spheroid of revolution

$$
\begin{aligned}
N_d &= \frac{4\pi r^2}{r^2-1}\left(1-\sqrt{\frac{1}{r^2-1}}\,\sin^{-1}\frac{\sqrt{r^2-1}}{r}\right) \\
B_{\text{int}} &= \left(1-\frac{N_d}{4\pi}\right)4\pi M
\end{aligned}
\tag{8}
$$

where $4\pi M$ is the maximum remnant magnetization for the material, and $r$ is the ratio of the ellipsoid radius in the direction of revolution to the ellipsoid radius along the "thickness" of the object.

The magnet assembly shown in the earlier figures includes disk-shaped pole pieces to improve the field efficiency of the magnets. The magnets themselves are in a cusped-field configuration, and would de-magnetize one another to a large extent if the pole pieces were not present. The pole piece material used in these experiments was fabricated from standard A50 steel which has a magnetic permeability $\mu > 10^4$ up to $B \sim 1.2$ T, after which $\mu$ begins to fall off.

Two configurations of magnet assemblies were built during this project. The first used SmCo-26 magnets 0.750" in diameter, 0.187" thick, with a 0.125" hole on center for mounting on the shaft connecting the two pistons. The pole pieces in between the magnets were 0.250" thick, yielding a pitch for the assembled structure of approximately 0.440". The interior bore of the coil structure was 0.800". The coil structure included 0.110" thick A50 steel disk pole pieces between the coils and a symmetric 8-piece yoke around the outside of the coils. The coils themselves were wound from #22 AWG copper wire coated with varnish insulation; each coil consisted of approximately 80 turns wound on a thin 304 SS jacket. The yoke, the pole pieces, and the coil jackets served to maintain the spacing of the coils at the same 0.440" as the magnet assembly.

Initial tests with this configuration indicated that the design had been too conservative and that the resulting magnetic field strength was too large. Small azimuthal variations in the magnetization of the magnets were sufficient to pull the shaft off-center and pin it to one of the pole pieces in the coil assembly. The magnet configuration was then changed to use 0.500" diameter SmCo-26 magnets, each 0.250" thick, with a 0.187" hole on center to accommodate a thicker, stiffer, mounting shaft. The pole pieces between the magnets were also modified to mate to the thicker, smaller magnets.

After modification, the final free piston shaft assembly weighed approximately 148 gm. Tests of the magnet-coil assembly with a rotary driver and a rotary-to-linear coupler on the free piston shaft indicated output voltages of 6-8 V from the center coils in the assembly and 3-4 V from the end coils.

A full optimization of the magnet-coil assembly was not performed during this project. Such an optimization would include considerations of coil packing density (square wire cross section), heat treatment of the pole pieces, and radial shaping of the magnets, coils, and pole pieces to use the flux generated more effectively. The final component of a full optimization would be to consider the starting mode of the generator and the possibility of using the magnet-coil assembly for this function.

### *2.4 Engine and Engine-Generator Tests*

The initial test on the engine system was performed on a unit that had a dummy mass on the piston, in lieu of a magnetic core. The shaft connecting the pistons, forming the single free-piston, was a 3/16" diameter steel rod. The center of this rod had a 100 gm aluminum mass held in place with two set screws. After only a few seconds of operation, it was found that:

- The mass could not be tightened firmly enough to prevent it from traveling along the length of the shaft;
- The 3/16" rod was too small a diameter to keep from flexing (bowing) during operation;
- After only a short period of operation, the bowing became a permanent deformation. The deformation of the shaft led to the quick demise of the first test unit. The bend in the shaft stuck in the shaft bushing, preventing the engine from running.

After these initial findings, the engine was modified to take a 1/4" diameter stainless steel shaft with a more permanently fixed dummy mass. Once this system was assembled, it was again run for up to several minutes at a time. The short duration of these runs was a result of the piston over-traveling, causing the piston skirt to run into the frame at the base of the cylinder. This occurred at the bottom of the stroke, causing the piston to partially tear away from the connecting rod, and leaving a hole in the top of the piston. With the hole, the piston was unable to compress the mix, and the engine died.

To alleviate the skirt end of the piston from crashing into the frame, a piston relief was cut into the frame. Tests of the engine after this modification indicated that other stroke length controls would be needed. The pistons now over-traveled into the cylinder, causing the pistons to "crash" into the head. Though not catastrophic in the short term, after several minutes of running, the engine would begin to lose compression as the top of the piston was deformed. After approximately 5,000 strokes ( run time ~1 minute), the engine would lose enough compression to quit running.

The results of these tests led to a complete redesign of the piston and magnetic core assembly. The redesigned system included 1/4" diameter shafts as connecting rods. These fed through the frame and mated with the magnetic core assembly, which included travel limiters. The core assembly was made of 1/2" thick aluminum, flared at the frame ends to 1" diameter. This flare had thin rubber "bumper" built into it that prevented damage in the event of over travel (see Figure 2). This system worked well, and no damage to the pistons or shaft has been observed since the modifications. Unfortunately, because of the increased diameter of the shafts and the lack of room in the system to include any seals, the leak rate in the mix gallery went up. The engine began to run only when "flooded." As the overly rich mixture in the gallery was expended, the system became unstable and cut out after only a maximum of two to three minutes.

Because run times longer than about three minutes were impossible to obtain without a redesign of the system, data gathering was extremely difficult. Data under varying load and operating conditions were particularly hard to gather. However, over short run periods some data were collected with the generator attached to various fixed power loads. An example of the characteristic waveform from the generator into a 50 ohm load is given in Figures 6 and 7.

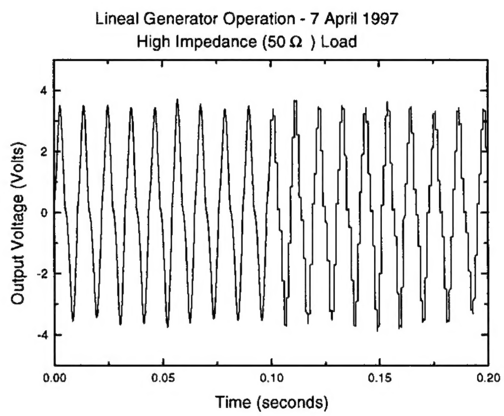


*Figure 6. Typical generator output into high impedance load.*

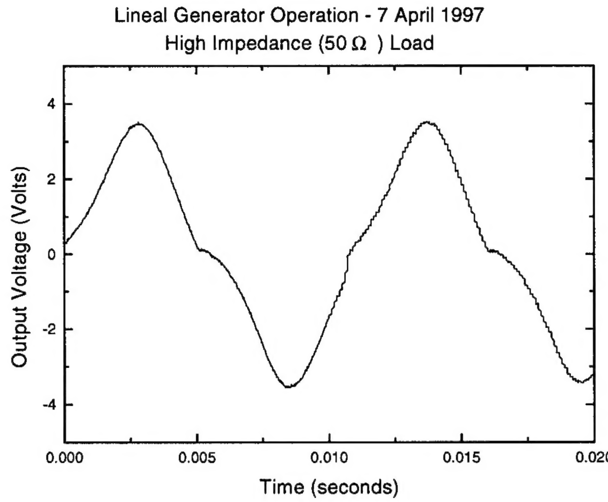


*Figure 7. Expanded scale view of generator output.*

Note: the irregularities on the trace lines of both figures are artifacts of the data acquisition system used to collect them.

Though these data are not to be considered representative of a correctly operating system, they do indicate the output is reasonably uniform in phase and amplitude. They also indicate that the operation of the lineal generator as a driven resonate mechanical system is a valid concept. The calculated operating frequency of the device as assembled was 90 Hz. As the data show, the real operating frequency was ~93 Hz.

Test runs performed into lower impedance loads indicated that the operating frequency remained constant into loads down to 2 ohms. At impedances of 1 ohm or less the engine would not run. Because the short operating times of the engine made collection of data through the acquisition system very difficult, these results are based on the observation of the operator and are not presented here in graphic form.

## 3.0 Conclusion

The most difficult problem faced in the development of the lineal generator was balancing the fuel and air mix between cylinders. The carburetors used in the prototype models were simple hobbyist units taken directly from the engines used to build the devices. While suitable for single cylinder engine operation, they proved nearly impossible to balance and became unstable after short periods of operation. This problem could be solved by incorporating a metered fuel injection system into the design. This "smart" aspiration system would also lessen the power wasted during unloaded periods of operation and regulate engine power output under loaded conditions.

Another problem encountered during the development of the lineal generator was timing control. Because the engine is diesel cycle, the temperature of the cylinders directly affects the engine operation. As the combustion chamber temperature rises, the timing becomes more "advanced." Combustion occurs sooner on the compression stroke, changing the operating characteristics of the engine and hence, the generator. Most of

the thermal control, and therefore the timing control, in model engines falls to the fuel mix. The rapid vaporization of the fuel within the cylinders as it is ingested cools the combustion chamber enough to prevent seizing of the piston. Once thermal equilibrium has been reached, assuming the air-to-fuel ratio remains constant, the engine will operate in a stable fashion. For typical unmodified model engines, this occurs in less than a minute. Because fuel mix regulation proved to be a major issue in the lineal configuration, timing also proved difficult to regulate and the engines remained thermally unstable. Though no seizing or other heat related damage was ever observed, the engines often would not run unless the glow plugs remained on. This indicates that the engine mix remained incorrect during operation, overcooling the cylinders. Again, metered fuel injection regulated in part by thermal monitors would greatly enhance the stability of operation of a diesel cycle lineal generator.

## 4.0 Recommendations

Because the two major deficits were centered on aspiration and the resultant timing control, the focus of initial improvement efforts will be on these aspects. The issue of timing, for the short term, is likely to be handled by moving from the diesel cycle design to an Otto cycle two-stroke. An Otto system utilizes spark ignition, and therefore timing is more easily controlled. Ignition timing can be both advanced and retarded electronically, making system control simpler in a small unit. Each of the problems encountered during the development of the lineal generator can be rectified through careful engineering. SAIC is likely to pursue further development of this concept, because the lineal generator represents a major step forward in the development of compact, lightweight man-portable power generators. The major emphasis on future models will be in the area of systems controls.

## List of Participating Technical Personnel

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